Low energy neutrino physics at the intensity frontier

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Opportunities in low energy neutrino physics...
...that I won't be talking about

- Oscillations
- Neutrino magnetic moment
- Strange spin component of the nucleon
- Geo neutrinos
- Solar neutrinos
- Supernova neutrinos
- Absolute neutrino mass
- Neutrinoless double beta decay
- Beta beams
- ....

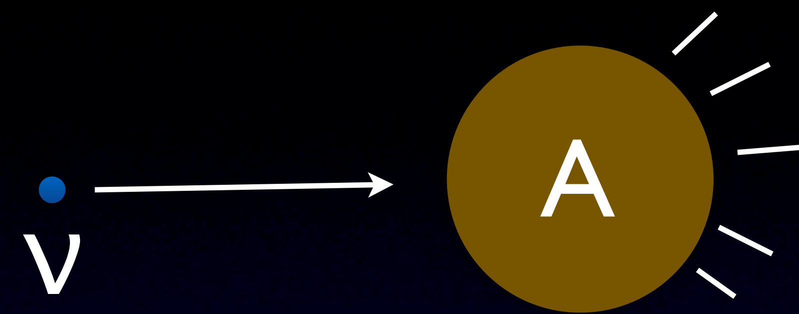
Other opportunities with low energy intensity frontier neutrino sources

Opportunities in low energy neutrino physics...
...that I will be talking about

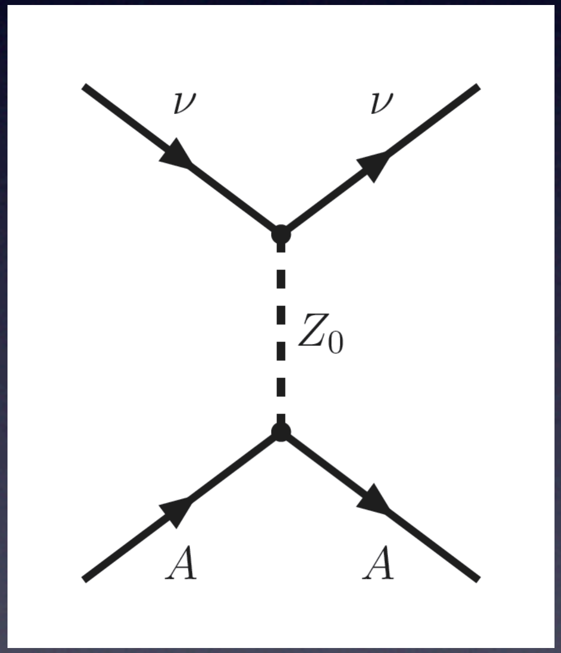
- Coherent neutrino-nucleus scattering
  - Why is it important?
  - How do you detect it?
  - Physics reach
- Neutrino cross sections important in astrophysics
- $\sin^2\theta_W$ with ν-e scattering

Coherent neutrino-nucleus scattering

$$\nu A \to \nu A$$



Coherent ν-A elastic



The total scattering amplitude can be approximated by taking the sum of the amplitudes of the neutrino with the individual nucleons when the momentum transfer is small.

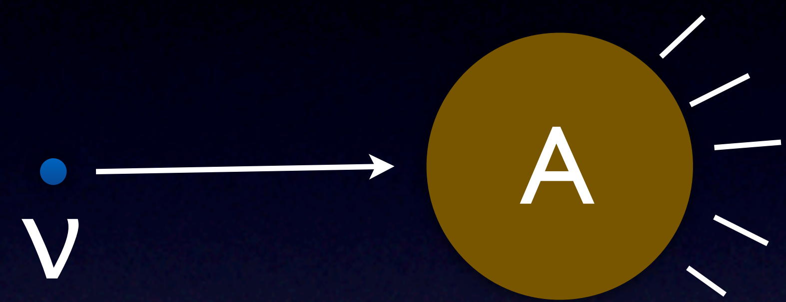
$$\frac{d\sigma}{dE} = \frac{G_F^2}{2\pi}\frac{Q_w^2}{4}F^2(2ME)M(2-\frac{ME}{k^2})$$

$$\text{Coherence condition : } E_\nu < \frac{1}{R_N} \simeq 50 \text{ MeV(for typical nuclei)}$$

A process well-predicted by the SM with a small theoretical cross section uncertainty (~5%).

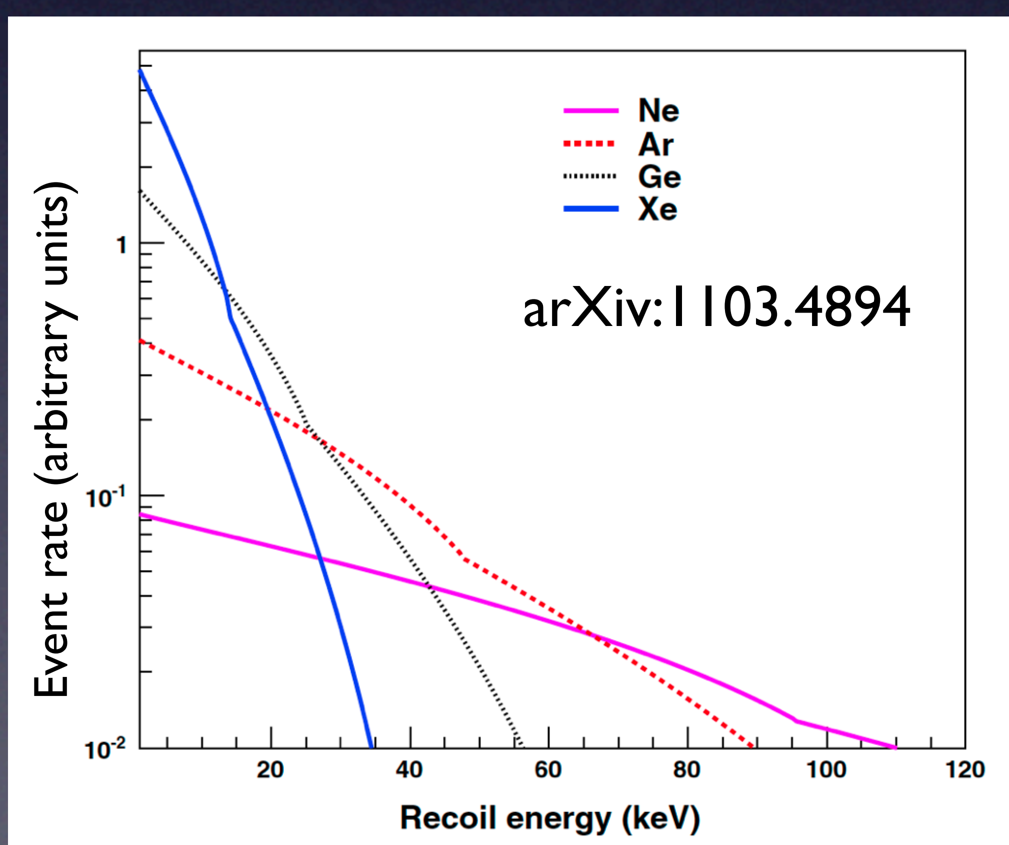
An unobserved process with a large cross section ...and a tiny signature

$$\nu A \rightarrow \nu A$$



In the few-50 MeV range:

- Coherent ν-A elastic $\sigma \sim 10^{-39}$ cm^2
- ν-A charged current $\sigma \sim 10^{-40}$ cm^2
- ν-p charged current $\sigma \sim 10^{-41}$ cm^2
- ν-e elastic $\sigma \sim 10^{-43}$ cm^2



Very low energy (WIMP-like) recoils

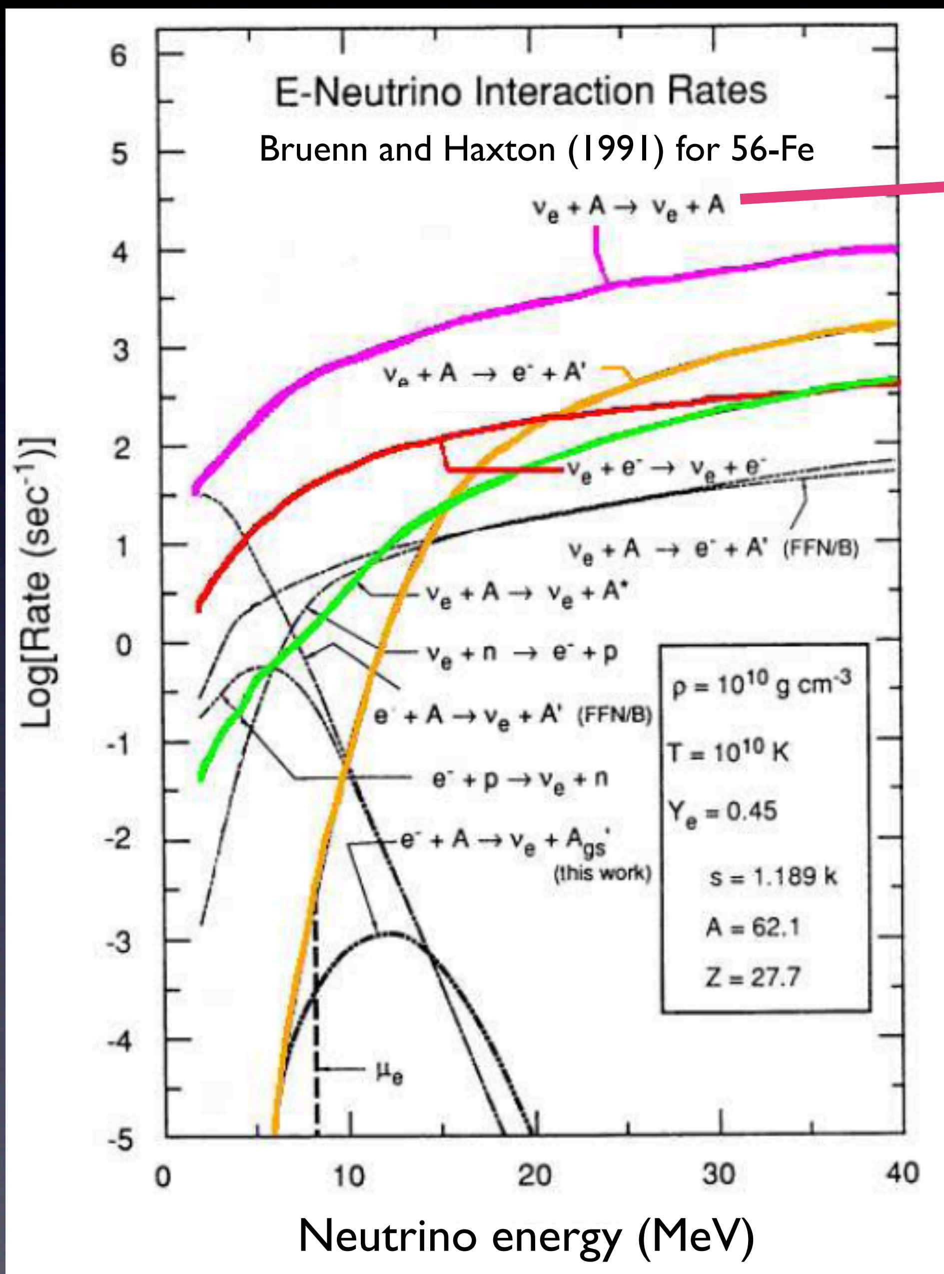
Recoil energies for stopped-pion neutrino source

Why is coherent neutrino-nucleus scattering interesting?

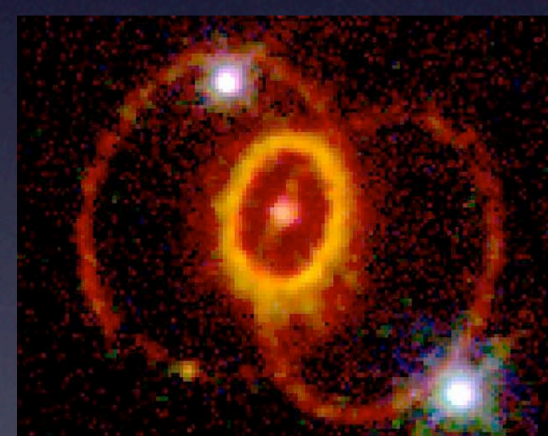
- This process has never been detected.
- Differences from Standard Model prediction could be a sign of new physics.
- Supernova process and burst/diffuse neutrino detection.
- Non-standard neutrino interactions.
- Weak mixing angle.
- Neutrino magnetic moment.
- Neutron radius (w/ neutrinos!).

Core-collapse Supernova

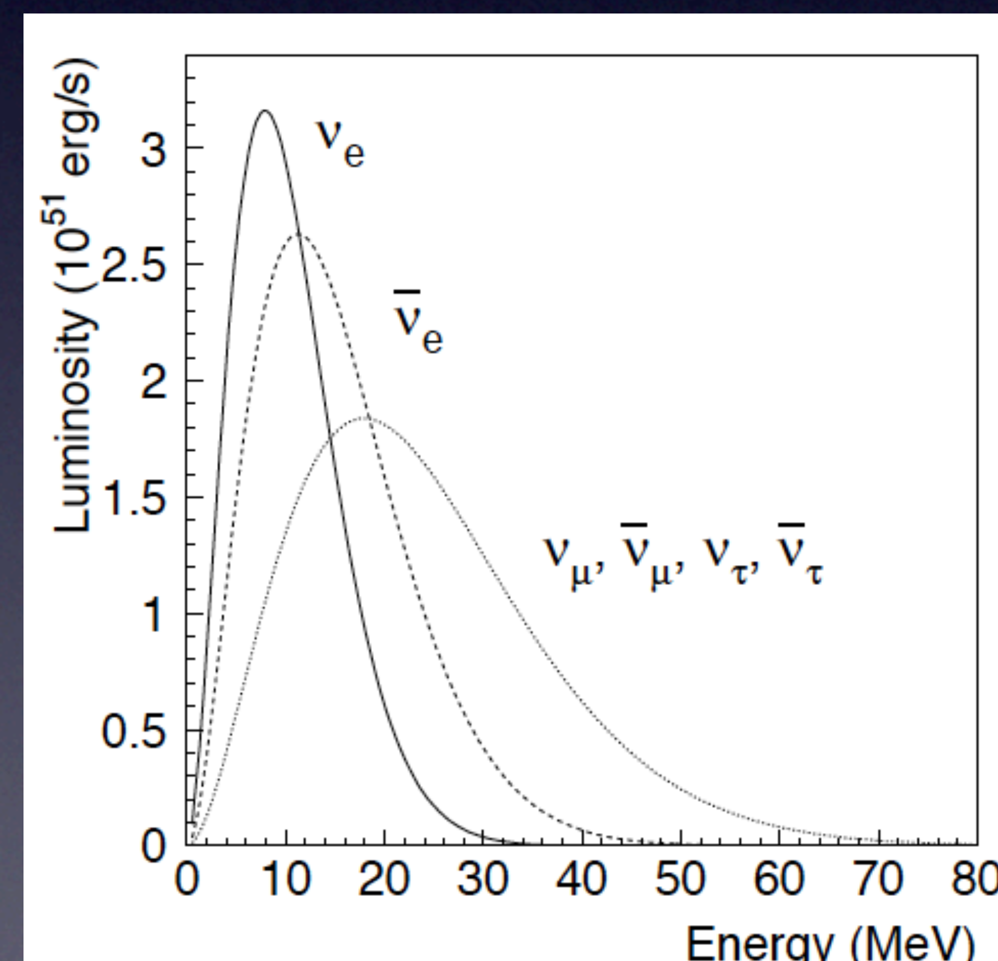
Neutrinos carry energy (10^{53} ergs, 99% of total) out of the star before anything else.



The dominant interaction, coherent neutrino-nucleus scattering, has never even been measured before!



SN1987a

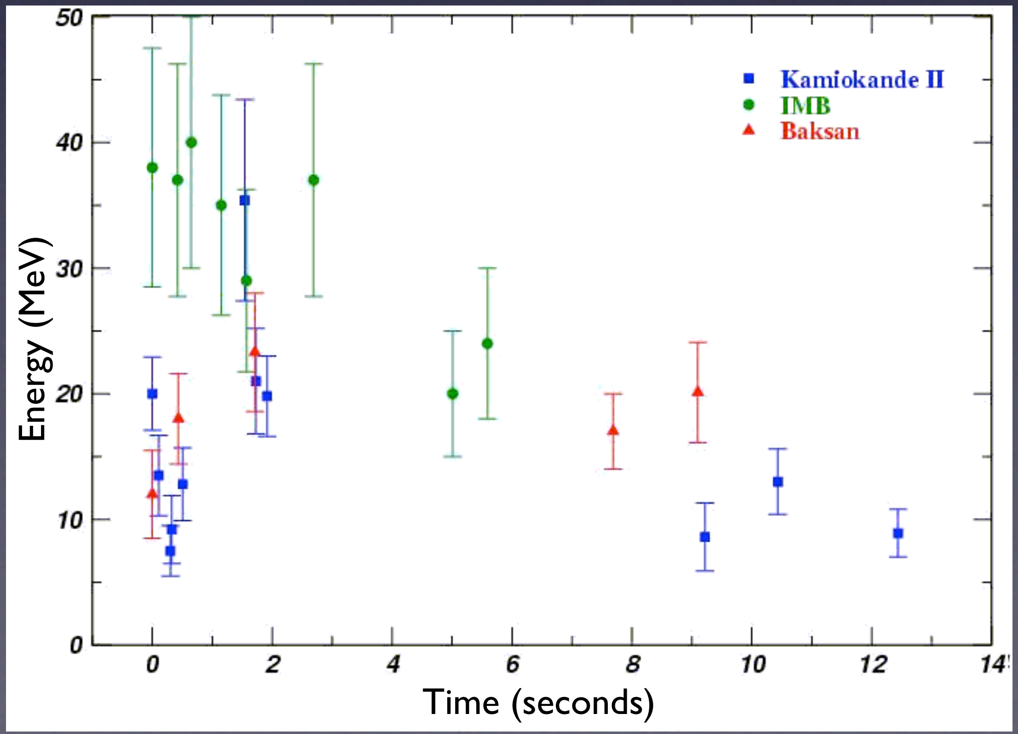


Core-collapse supernova neutrino spectra

All 6 flavors for coherent neutrino-nucleus!

An aside:
Neutrino cross sections for astrophysics

- Cross section measurements at low energy (~0-50 MeV) on various nuclear targets are essential to understanding core collapse supernovae and the neutrino spectra emitted.
    - How were the elements from iron to uranium created?
    - How does a core collapse supernova take place? Recall that we have problems getting a supernova to explode via simulation.
    - Interpreting supernova burst/diffuse signal on Earth.
- An experiment at an intensity frontier decay at rest source can perform measurements of the most relevant neutrino cross sections: ^{2}H, C, Ar, O, Pb, Fe.



The neutrinos from the next one are already on their way (literally). How do we interpret the spectrum w/o cross section info?

The most relevant cross section on arguably the most important nucleus of all, iron, has only been measured with ~40% precision!

Need more data!

Non-Standard Neutrino Interactions

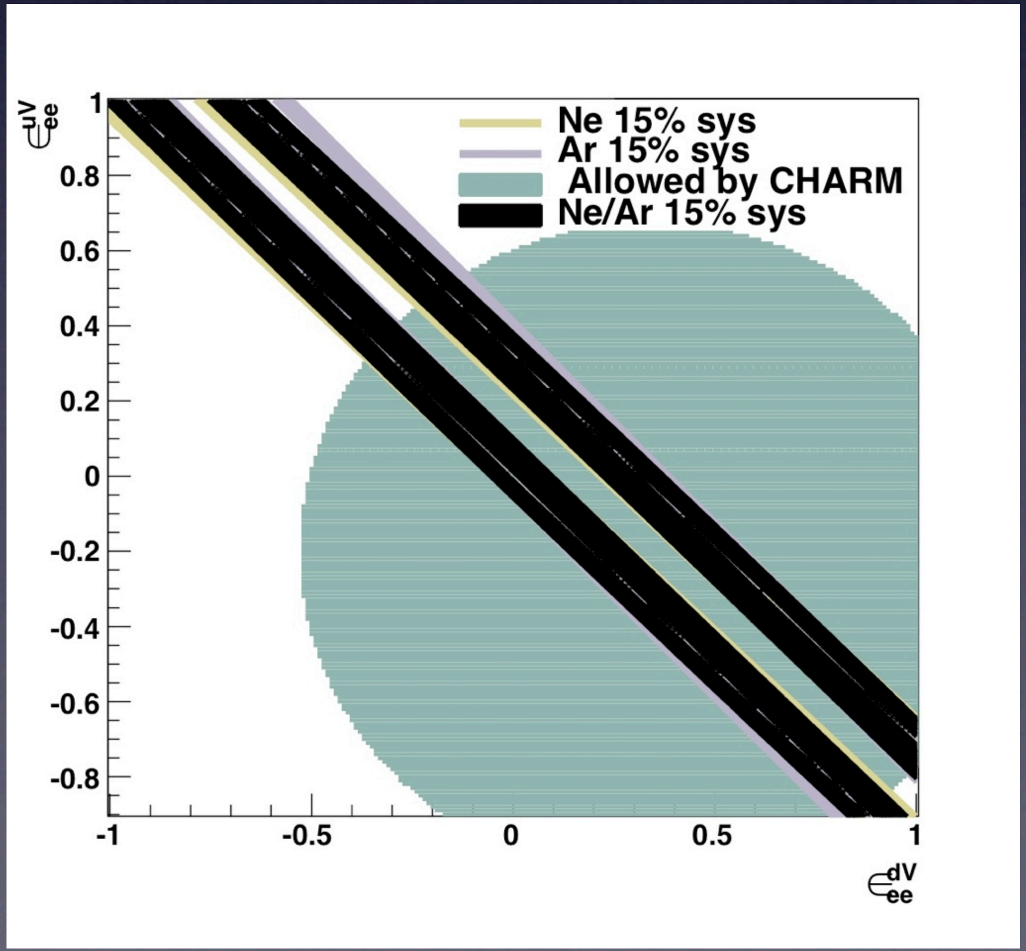
Planned and existing precision experiments are not sensitive to new physics specific to neutrino-nucleus interactions.

The signature of NSI is a deviation from the expected cross section, shown here with NSI vector coupling constants added.

$$\frac{d\sigma}{dE} = \frac{G_F^2 M}{\pi} F^2(2ME) \times (Z(g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV}) + N(g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV}))^2$$

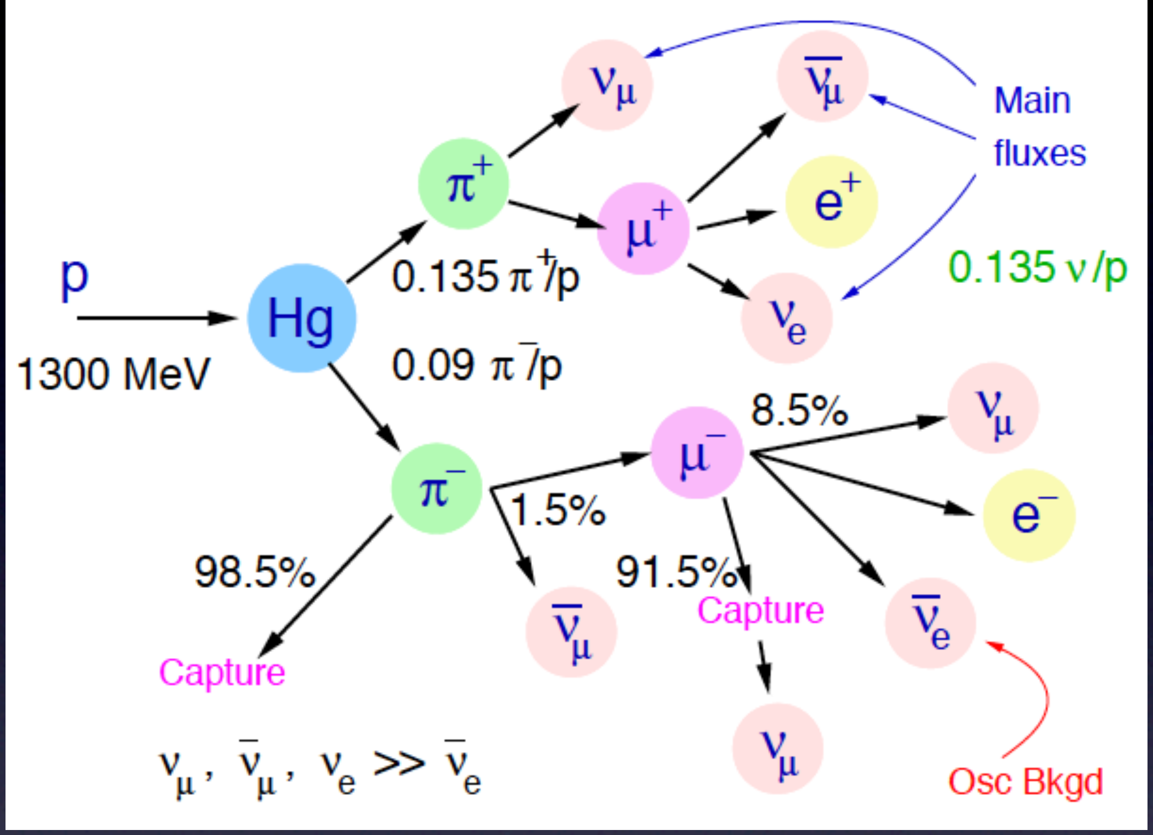
Non-standard interactions are often poorly constrained:

A coherent neutrino measurement (with just 100 kg-year exposure at SNS) on argon/neon consistent with the SM would provide an order of magnitude improvement on existing limits.

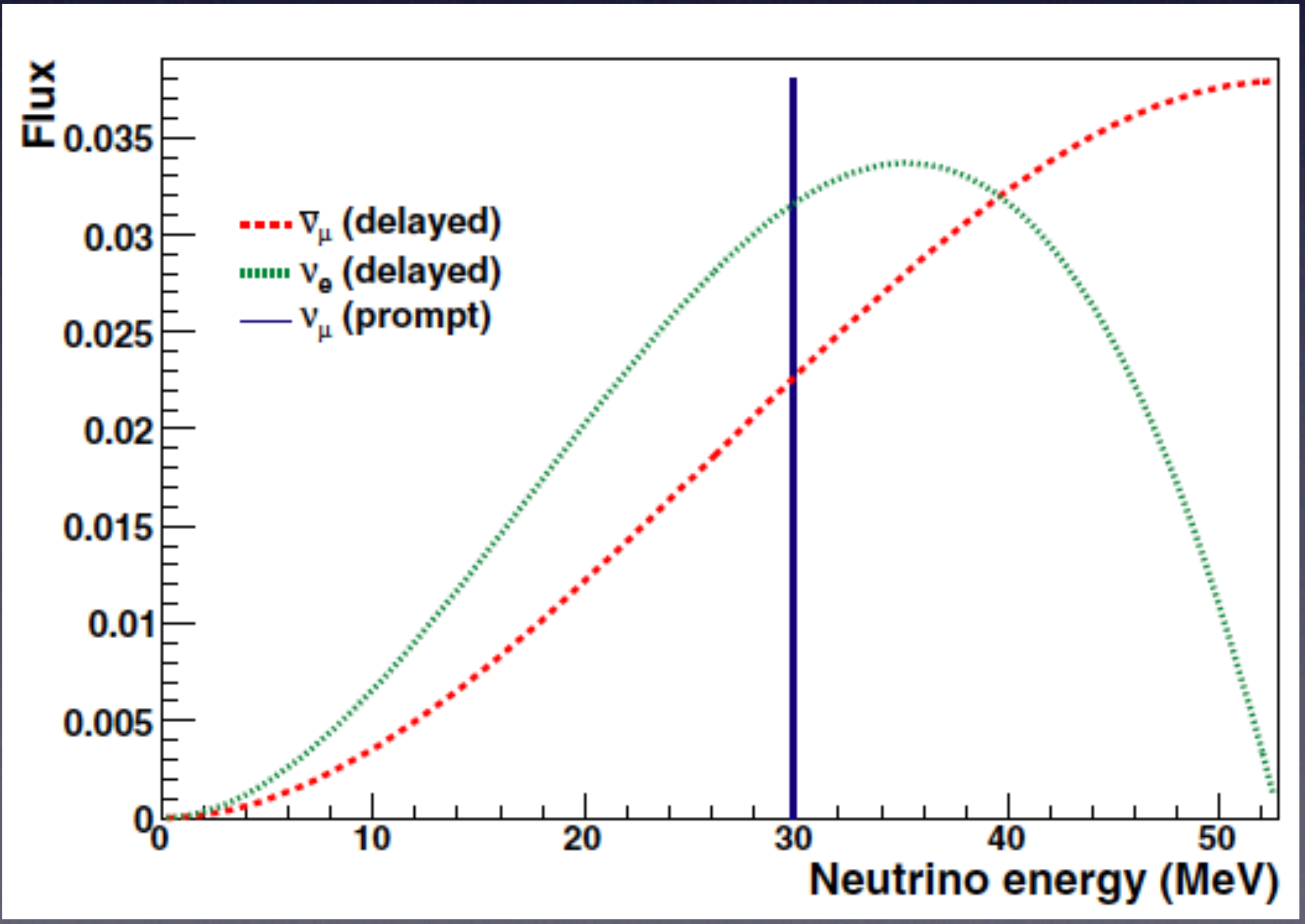


Opportunities at the IF with a decay-at-rest source

- A 800 MeV, 1 MW accelerator can provide 4E22 ν/flavor/year.
- Beam timing provides an *in-situ* background measurement and background mitigation in general.



For 1300 MeV protons on Hg (nucl-ex/0309014)



Prompt

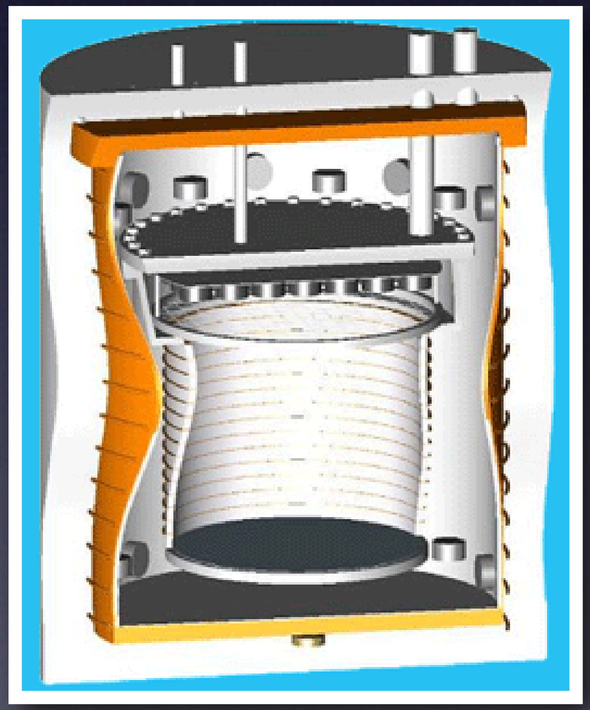
$$\pi^+ \longrightarrow \mu^+ \nu_\mu$$

$$\mu^+ \longrightarrow e^+ \bar{\nu}_\mu \nu_e$$

Delayed

Low energy detection techniques

WIMP detectors are sensitive to keV-scale recoils...
and pretty much any technology will do.

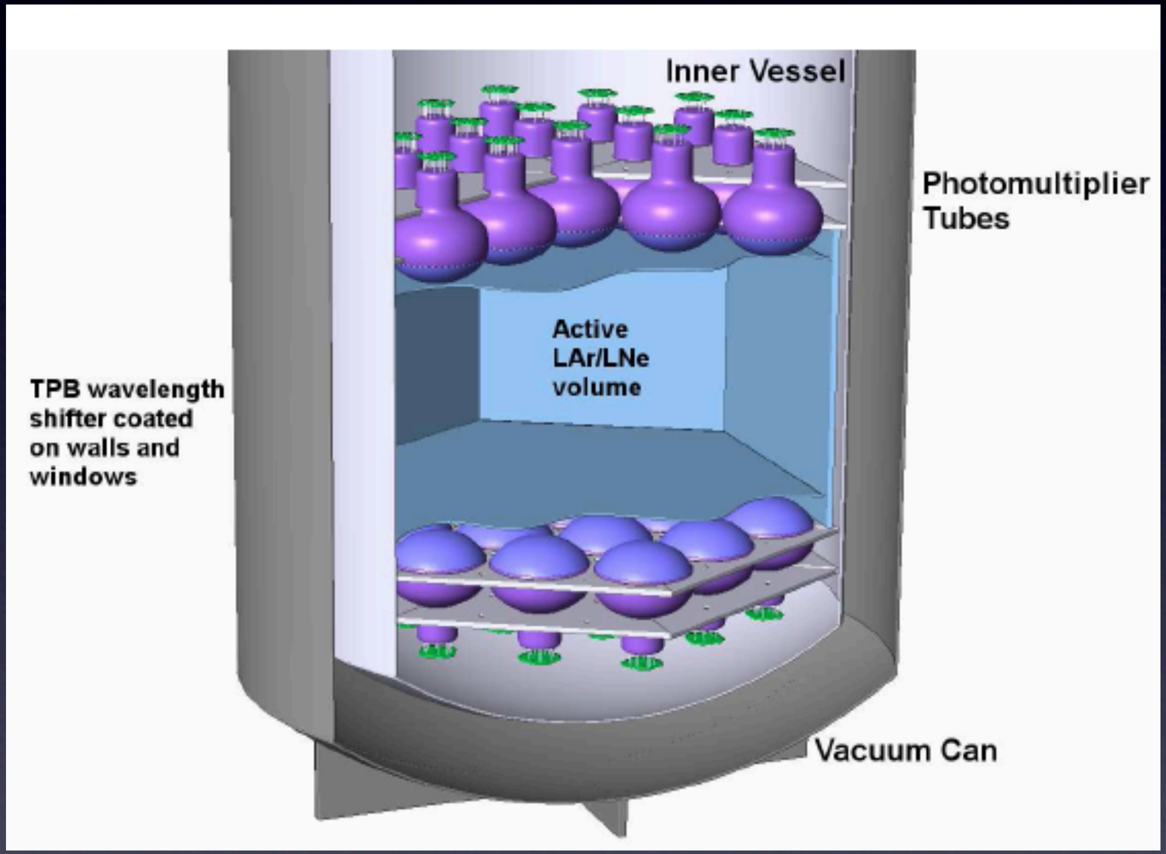


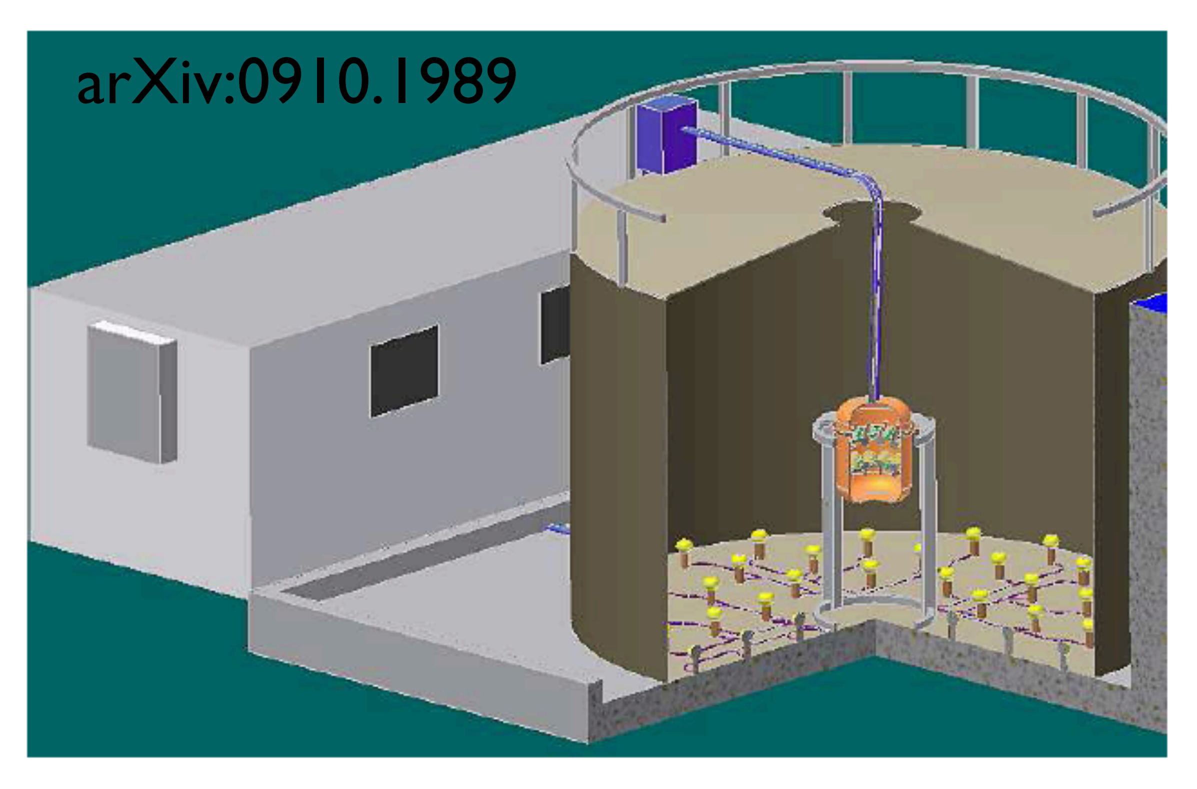
XENON (~3 keV)

CDMS (~7 keV)

COUPP (~5-10 keV)

Coherent Low Energy A Recoils = CLEAR at the Spallation Neutron Source

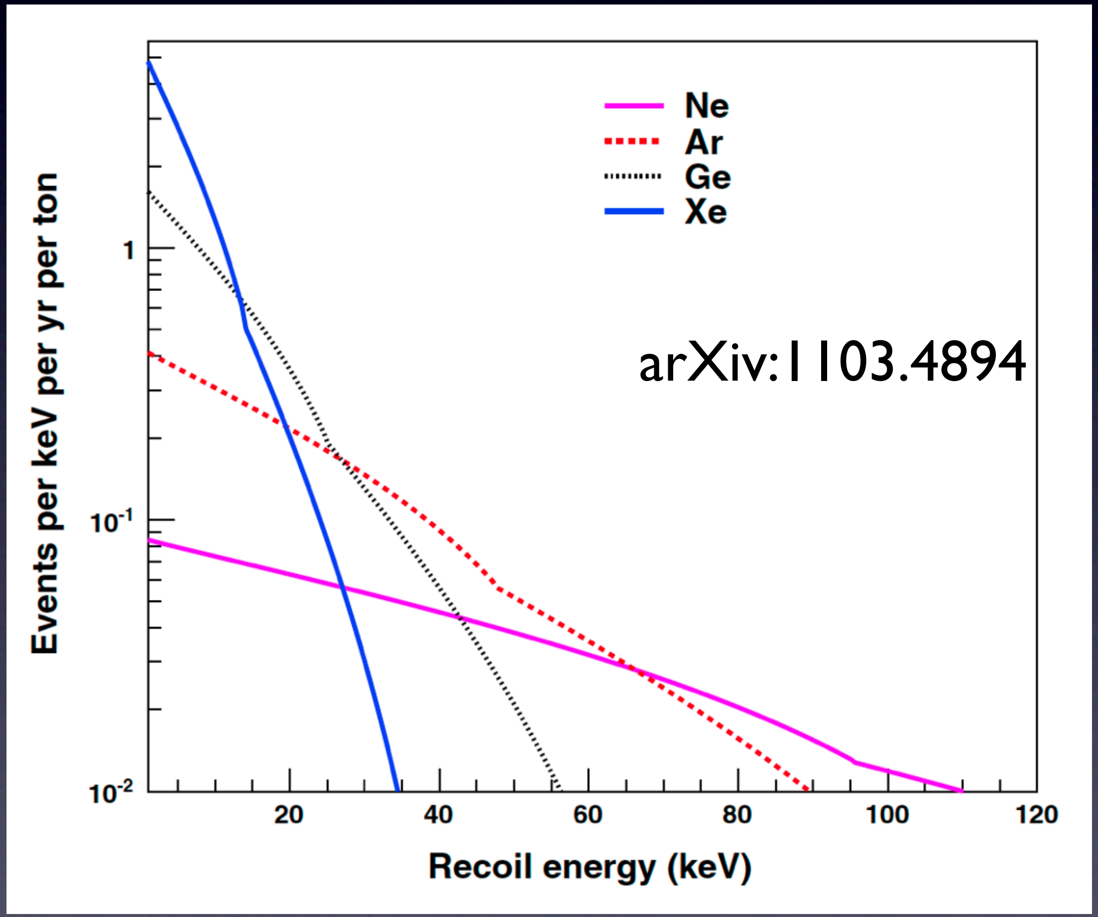




- CLEAR would be on the surface, 46 meters from the stopped-pion neutrino source at SNS.
- Active LAr (LNe) volume = 456 (391) kg.
- 200-1000 signal events expected per year, depending on analysis threshold and target.

Coherent scattering with DAEdALUS

- DAEdALUS will provide 4E22 ν/flavor/year from a decay-at-rest source.
- A 10 kg fiducial mass Ge-based WIMP-style detector within 20 m of the neutrino source could collect >1000 events in 5 years.
- WIMP detectors at DUSEL could make a first observation of the coherent interaction with a negligible effect (~10%) on the WIMP search.
- An aside: DAEdALUS combined with an ultra-large water detector can provide a 0.24% measurement of the weak mixing angle via neutrino-electron elastic scattering.

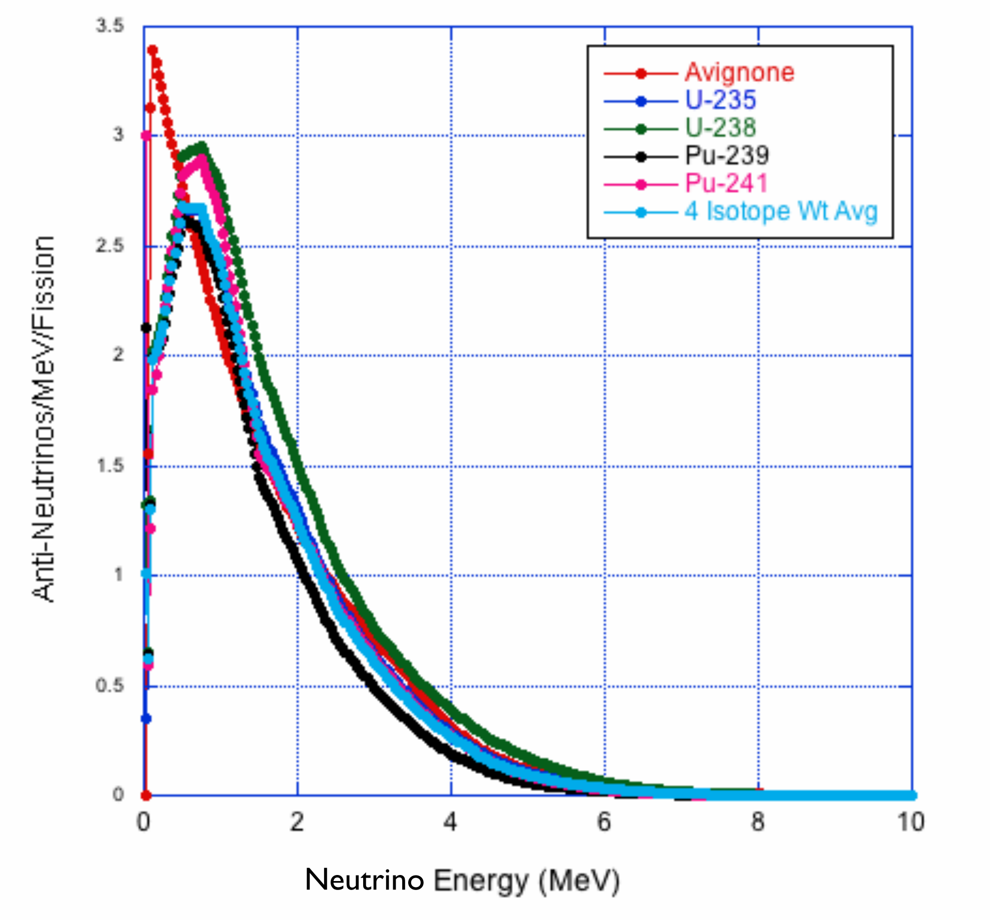


Coherent scattering rate at 1.5 km from the decay-at-rest source

See Karagiorgi talk for an introduction to DAEdALUS

Opportunities at the IF: coherent scattering with a reactor source

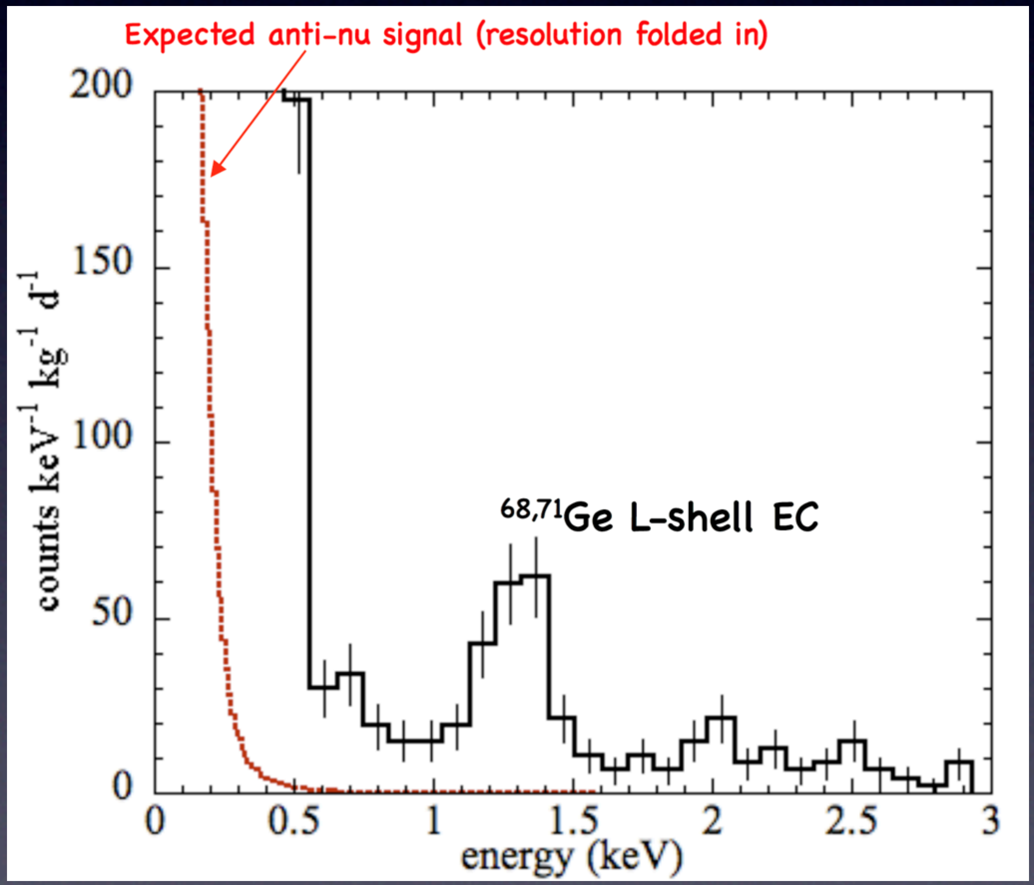
- Nuclear reactors are intense sources of neutrinos, producing 2E20 ν/second/GW.
- Neutrino interactions are competing with radioactive decays and cosmic-ray induced backgrounds at these energies (0-8 MeV).



Reactor neutrino energy spectrum

COGENT
and coherent neutrinos

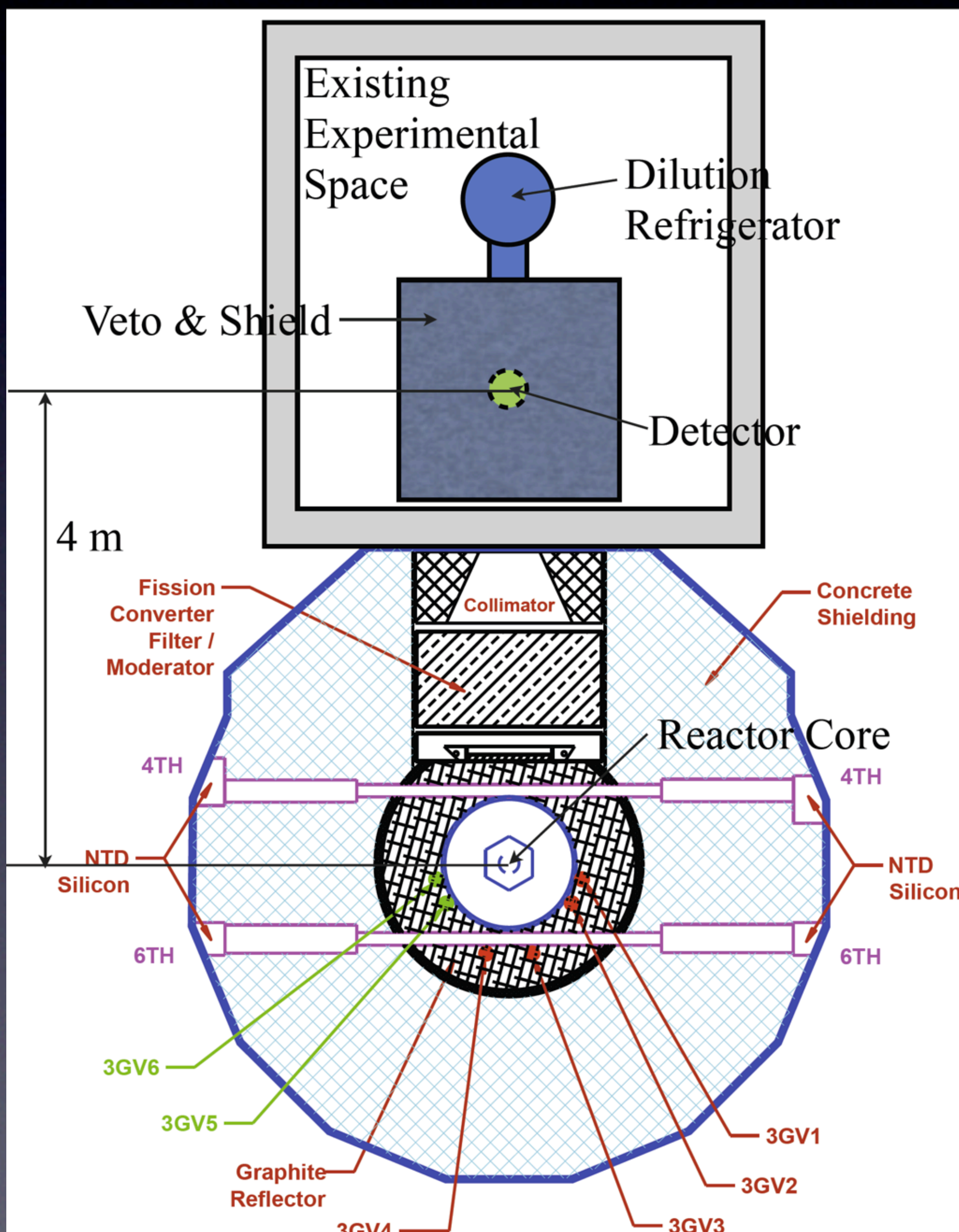
- COGENT (Ge-based) is an experiment with applications in $0\nu\beta\beta$ decay (MAJORANA), light dark matter direct, and coherent neutrino detection.
- Prototype detector ran 20 m from ~1GW reactor core (SONGS).
- Need energy threshold and noise improvements for coherent neutrino detection.
- Improvements may allow coherent detection soon!



Observed spectrum by COGENT

Thanks to J. Collar!

Ricochet
and coherent neutrinos



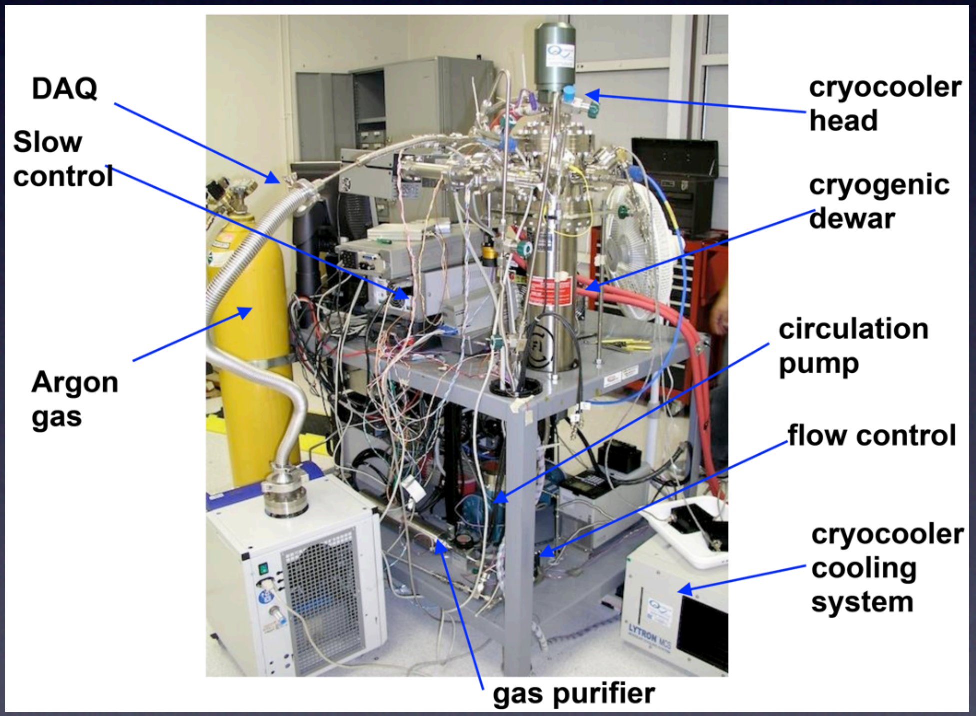
Envisioned experimental setup

- An experiment to discover coherent scattering at MIT's 5.5 MW reactor using Ge crystals and phonon detection.
- The name of the game is background/noise mitigation as ~4 signal events/kg/day are expected with a phonon-only ultra-low 100 eV threshold.

Thanks to E. Figueroa-Feliciano!

More experiments and ideas at the intensity frontier

- Coherent detection at Fermilab using the decay at rest component of the Booster Neutrino Beam and a WIMP-style detector.
- TEXONO (Taiwan reactor-based; CsI(Tl) scintillating crystal)
  - Neutrino magnetic moment and coherent scattering sensitivity.
- Dual phase LAr for reactor coherent detection (LLNL)



- C°sI (SNS; CsI scintillating crystal)
  - Coherent detection.
- ν-SNS (SNS; water, liquid scintillator, iron, ...)
  - Cross sections for astrophysics and SN terrestrial neutrino detection.
- ORLaND (SNS; water)
  - Cross sections for astrophysics and SN terrestrial neutrino detection. Oscillations.

Conclusions

- There is a lot of physics in coherent neutrino-nucleus scattering. The process hasn't even been observed before!
- Decay at rest and reactor sources also provide opportunities to measure neutrino magnetic moment, cross sections relevant for astrophysics, strange spin component of the nucleon, and $\sin^2\theta_W$.
- I haven't even mentioned sterile neutrinos (LSND/MiniBooNE), the reactor anomaly, or θ_{13}!
- Everything in this talk has featured proposed or existing experiments and technologies. That is, the opportunities in low energy neutrino physics are achievable at the intensity frontier. It is unfortunate that so many of the "free" neutrino sources currently in existence (see: reactors, DAR sources) are completely untapped.

arXiv: 1004.0310

Facility	Power	Proton energy	Time structure	Repetition rate
LANSCE (USA)	56 kW	0.8 GeV	Continuous	N/A
ISIS (UK)	160 kW	0.8 GeV	200 ns	50 Hz
SNS (USA)	$>$ 1 MW	1 GeV	380 ns	60 Hz
JSNS (Japan)	1 MW	3 GeV	1 μs	25 Hz
SPL (CERN)	4 MW	3.5 GeV	0.76 ms	50 Hz
ESS (Sweden)	5 MW	1.3 GeV	2 ms (1.4 μs)	17 Hz (50 Hz)

The past, present, and future of spallation neutron sources.
A rich neutrino physics program is possible with all of these.

Thanks

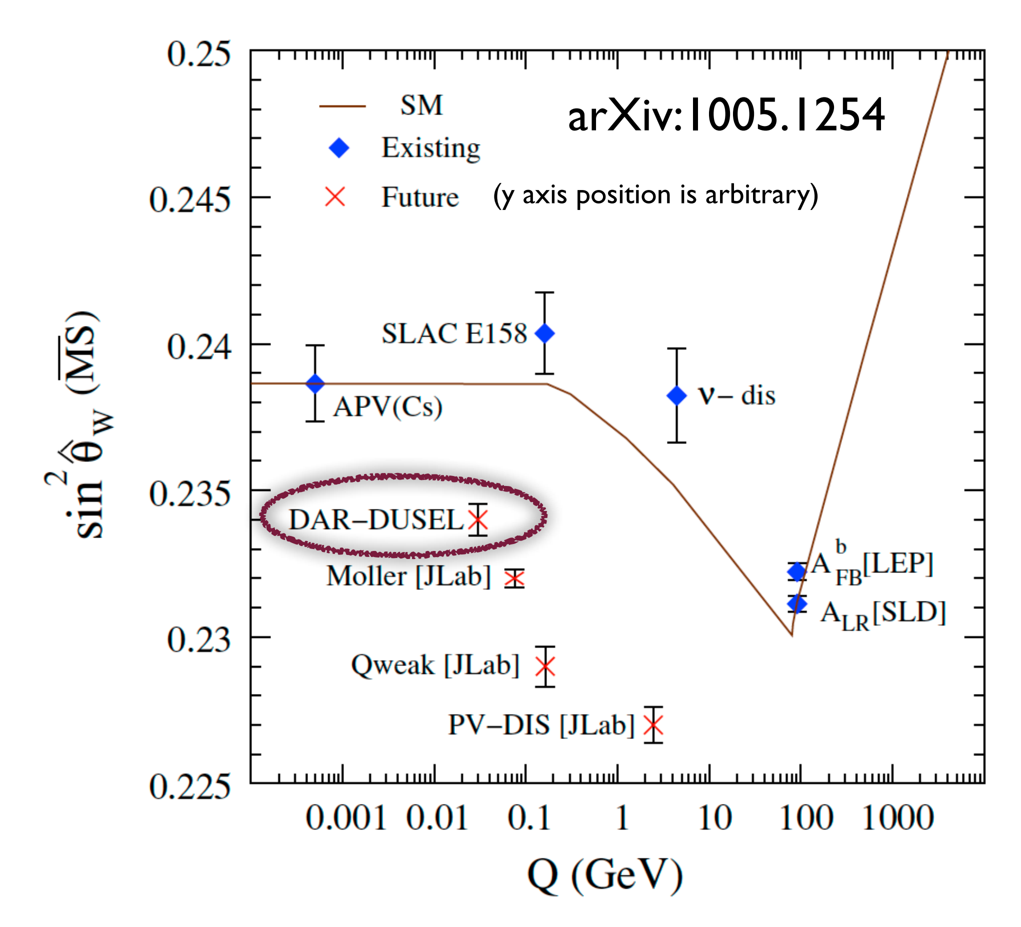
Thanks to:

Janet Conrad, Kate Scholberg, Enectali Figueroa-Feliciano, Sam Zeller, Juan Collar, Bonnie Fleming, Adam Bernstein, Jonghee Yoo.

Backup

The weak mixing angle with low energy ν-e scattering

- An intense decay-at-rest source, combined with an ultra-large water detector, can provide a measurement of the weak mixing angle via neutrino-electron elastic scattering.
- ~20 million signal events yields 0.24% precision on $\sin^2\theta_W$ at Q~0.03 GeV.



- Along with decay-at-rest $\sin^2\theta_W$ measurement possibilities, a ~1% precision measurement on $\sin^2\theta_W$ is also possible at a reactor using ν-e scattering.

Coherent scattering and the weak mixing angle

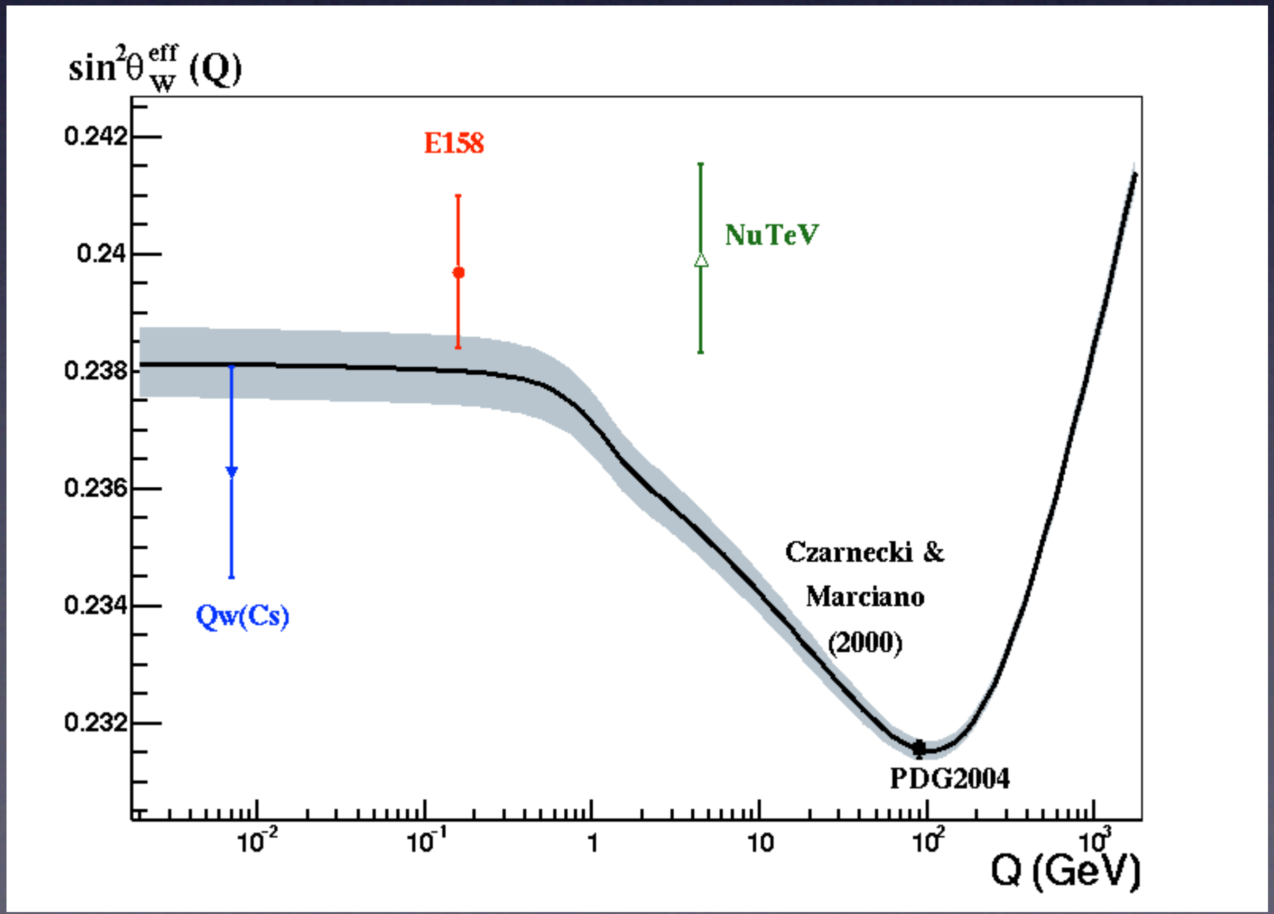
$$\left(\frac{d\sigma}{dE}\right)_{\nu A} = \frac{G_F^2}{2\pi}\frac{Q_w^2}{4}F^2(2ME)M[2-\frac{ME}{k^2}]$$

$$Q_w = N - (1 - 4\sin^2\theta_W)Z$$

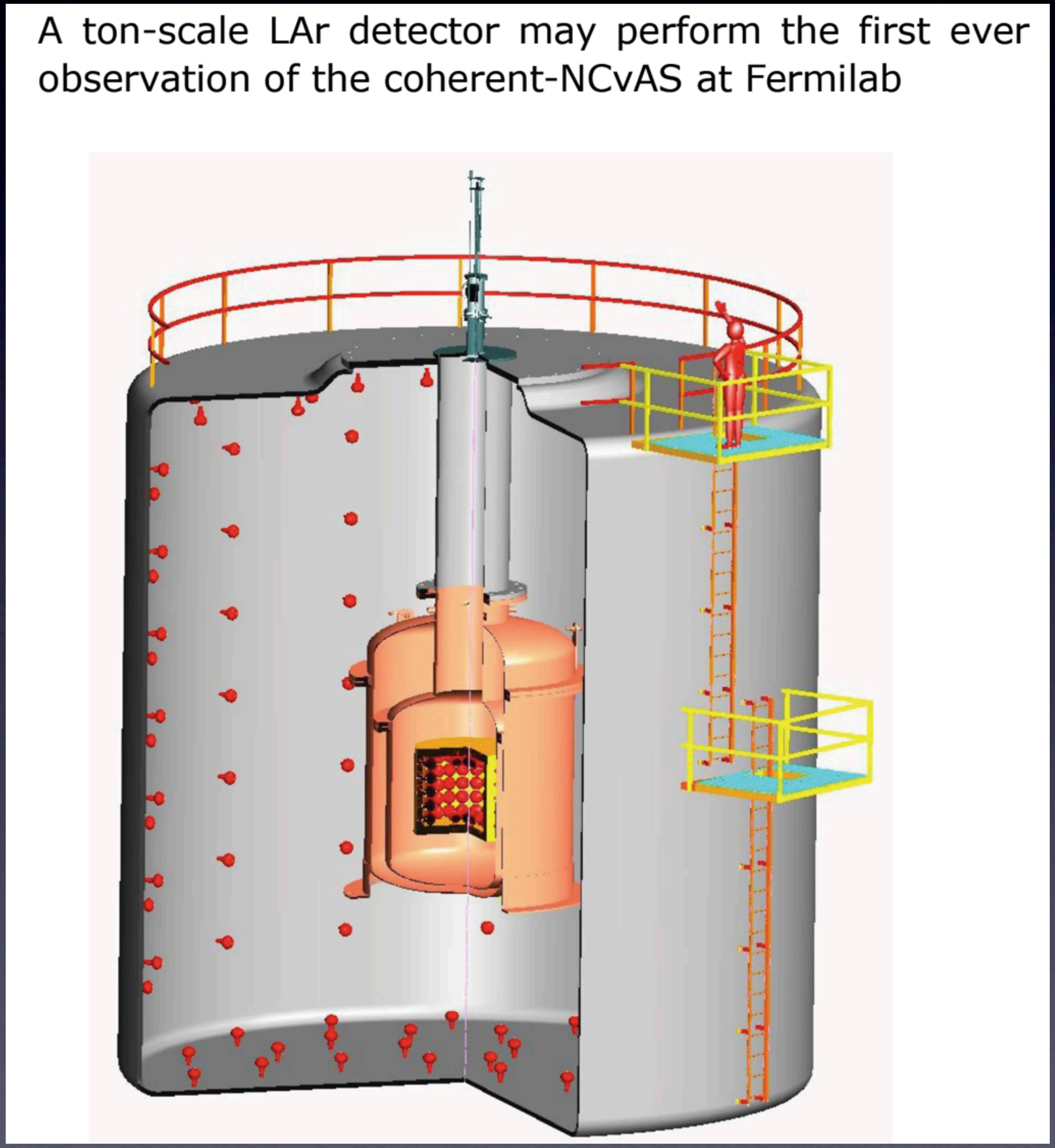
where Z is the number of protons, N is the number of neutrons, and θ_W is the weak mixing angle.

The weak mixing angle can be found by measuring the absolute cross-section.

A first generation experiment may not be competitive with precision APV and e-e scattering experiments. However, there are no other neutrino measurements near Q~0.04 GeV/c.

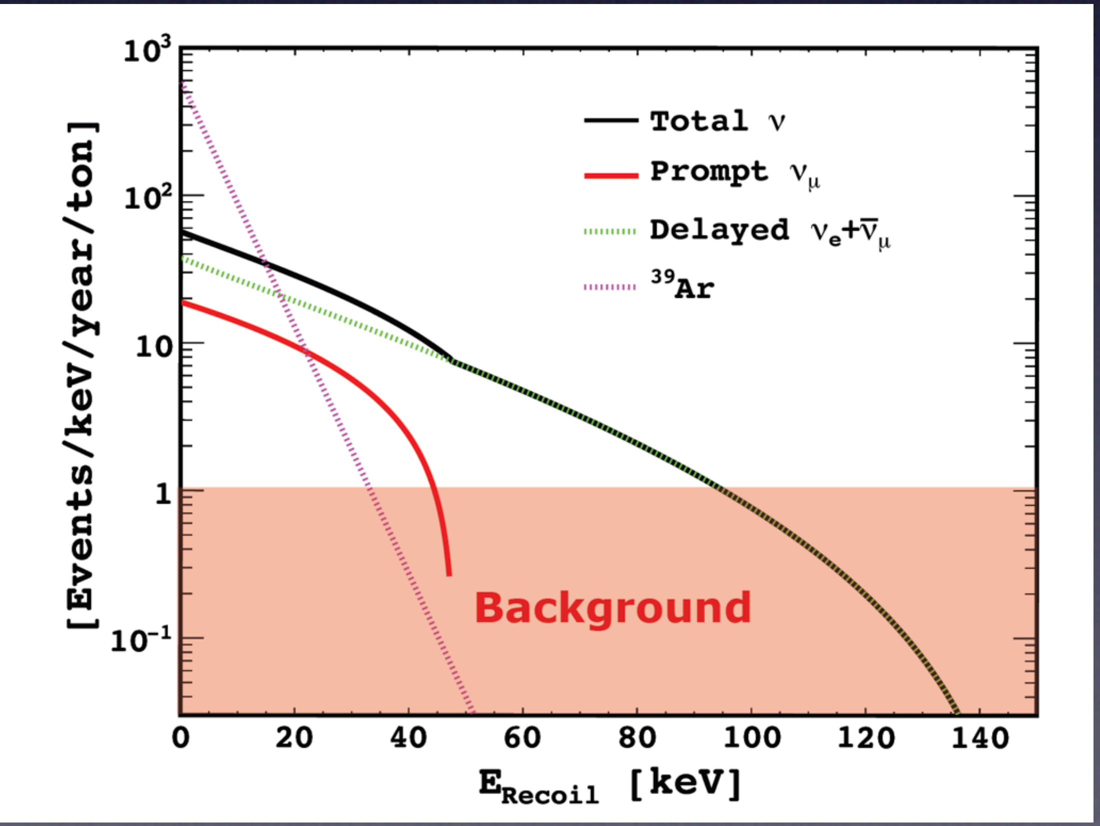


Coherent neutrino detection at Fermilab



Envisioned experimental setup

- There is a decay-at-rest neutrino component to the Booster Neutrino Beam, dominating at far-off-axis.
- A WIMP-detector-like single-phase Ar-based device could collect ~200 events/ton/yr at 20 m from the target.

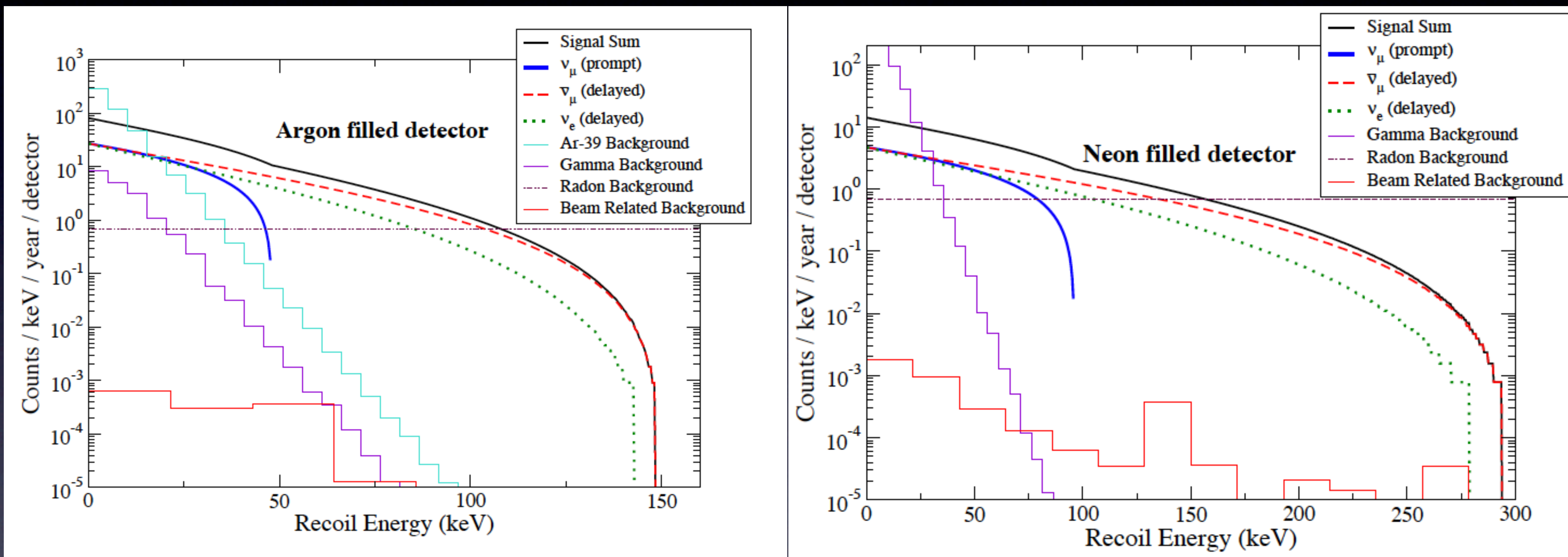


Event rate 20 m from BNB target

Thanks to J. Yoo for plots and information!

Backgrounds for CLEAR

Intrinsic, steady-state backgrounds are the main worry for CLEAR.
Nuclear recoils due to neutrons look like signal.

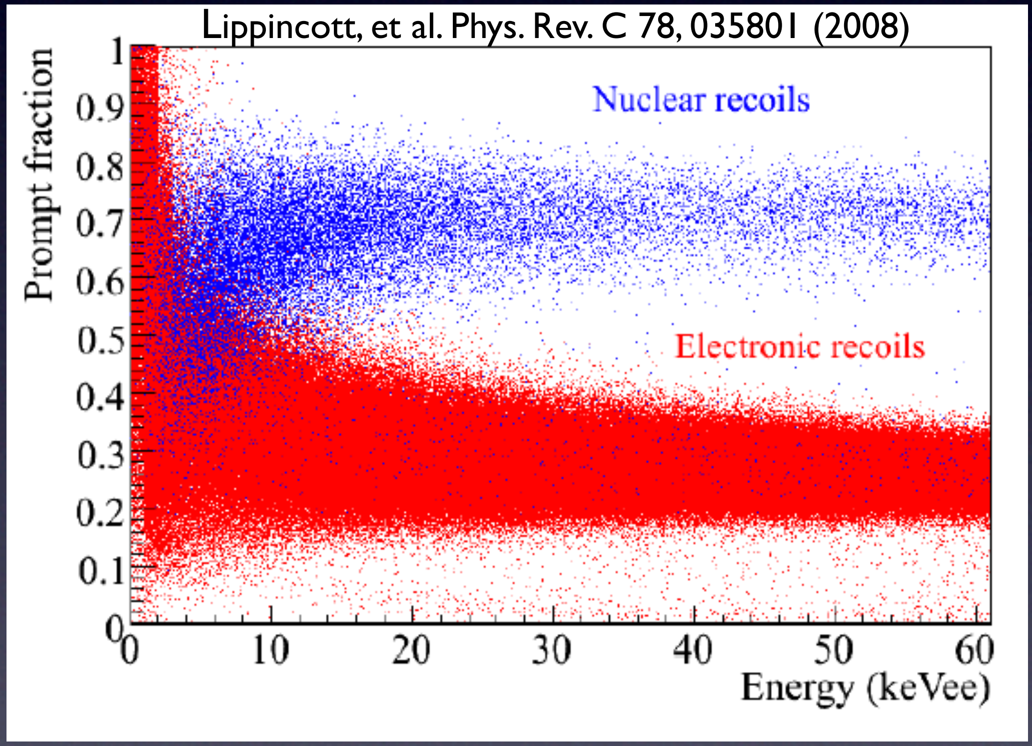


hep-ex: 0910.1989, with credit to K. Scholberg, J. Nikkel, T. Empl, and T. Wongjirad

Note that CR-related backgrounds are not plotted here.
They can be measured quite well during the beam dead time. However, the CR rate drove the CLEAR single-phase design (see: dead time for a two-phase).

Background mitigation

- A repetition frequency of 2000 Hz with a 100 microsec window gives a rejection of steady state background of 0.2 and knowledge of the steady-state rate. Fast scintillation signal from individual events can be known to within ~10ns
- Mitigation of backgrounds (see: WIMP-detection):
  - Ar-39 (beta) background:
    Neon, Xenon, or depleted Argon and Pulse Shape Discrimination (PSD), charge-to-light ratio in time in a dual phase detector.
  - Radon background:
    Mechanical scrubbing, HEPA filters, and radon-impermeable plastic.
  - Gamma backgrounds (238-U, 232-Th, 40-K):
    PSD, charge-to-light ratio in time in a dual-phase detector.
  - Beam- and cosmic ray-related:
    Shielding. Underground, these backgrounds will be much lower as compared to SNS. Expensive shielding/veto is probably not necessary with 150 mwe overhead.



PSD in argon

Singlet (short lifetime) and triplet (long lifetime) states are populated differently for nuclear and electronic recoils